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Final Report

NAG 6-103

**"Measurement of Atomic Oxygen in Diffuse Aurora
and Ion Density in the E-region"**

by

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E-region Studies

An ion mass spectrometer (IMS) was refurbished, calibrated and supplied to the University of Colorado payload (Dr. Charles Barth, P.I.) which was launched from White Sands in September of 1993 as NASA 33.062. The nose cone failed to deploy and there were problems with the ACS so the mission was declared a failure. However, the door covering the IMS deployed and the instrument obtained data. The launch occurred shortly after a payload carrying solar x-ray detectors was launched. Thus a small portion of the Colorado payload science was salvaged; namely, the NO^+/O_2^+ ratio to compare with the measured x-ray flux. Figure 1 shows the NO^+ to O_2^+ ratio vs. altitude. The behavior is typical of the E-region.

The Ion Mass Spectrometer was refurbished, calibrated, and flown on NASA 33.063. That flight from Poker Flat during conditions of high geomagnetic activity ($K_p > 7$) was a success in that all the instruments obtained data. The ion data has been reduced and the ratio of NO^+/O_2^+ is shown in figure 2. This data in the altitude region 100 to 130 km was reported at the fall meeting of the AGU and the summer meeting in Boulder of the IUGG in conjunction with the NO data and the solar x-ray flux. The ratio indicated the presence of large quantities of NO which were substantiated by the NO instrument. Using the parcel trajectory model of Killeen and Burns, the parcels of air between 105 and 115 km spend many hours in the aurora before arriving at the point in space where the rocket penetrated. Such enhancements in NO would explain a portion of the enhancement of NO^+ at the expense of O_2^+ . Figure 3 compares the ion mass spectra at 110 km at midlatitude quiet time with the high latitude active time. The O_2^+ peak is clearly suppressed with respect to NO^+ .

The Ion Mass Spectrometer was refurbished, calibrated and flown on NASA 33.064 from Poker Flat during conditions of magnetic quiet ($K_p = 2$). All the instruments obtained data and the NO^+/O_2^+ data are shown in Figure 4. Compared with the results obtained during the magnetic active period (NASA 33.063) the ratio is suppressed in the region above 110 km. The results of these experiments were reported at the Fall AGU meeting.

Diffuse Auroral Atomic Oxygen Measurements

A resonance fluorescence module (SARS) to measure atomic oxygen was fabricated, calibrated and supplied to the Aerospace Corp. payload on NASA 27.131 (Dr. Andrew Christensen, P.I.) which was launched from Poker Flat in February of 1994. The detector gain decreased dramatically after lift-off. Thus, the count rate had no calibration and was too low to give any meaningful results. The problem was traced in post flight examination to a failure in the high voltage potting compound. A new detector was purchased and the sensor refurbished and calibrated for flight on 27.138 and 27.139. On flight 27.138 the ACS unit malfunctioned and severely compromised the SARS data. Throughout the region of importance between 85 km and 110 km the sensor was in the wake region on the upleg. The sensor was recalibrated and flown the following year on 27.139, obtaining good data. Figure 5 shows the upleg and downleg oxygen densities. There is a suggestion of a slight enhancement on the downleg data. This was also the case in the original ARIA experiment.

A paper discussing the depletion of oxygen in the aurora was published in the Journal of Geophysical Research. The oxygen data from the initial ARIA flight and the one discussed above comprised a portion of the evidence indicating a local mechanism of depletion operating in the auroral region following auroral heating.

Papers and Presentations

Depletion of Oxygen in aurora: evidence for a local mechanism, (with A. B. Christensen and others), J. Geophys. Res., **102**, 22273, 1997.

Rocket observations of neutral and ionized nitric oxide in the polar thermosphere, (with Barth, Bailey and Kohnert), American Geophysical Union, Fall Meeting, San Francisco, December, 1994.

Coupling between Neutral and Ionized Nitric Oxide in the Polar Thermosphere, (with C.A. Barth and S. M. Bailey), IUGG Meeting, Boulder, July, 1995.

Comparison of two rocket observations of neutral and ionized nitric oxide with a time-dependent model, (with C. Barth and others), American Geophysical Union, Fall Meeting, San Francisco, December, 1995.

33.062 IMS NO⁺/O₂⁺

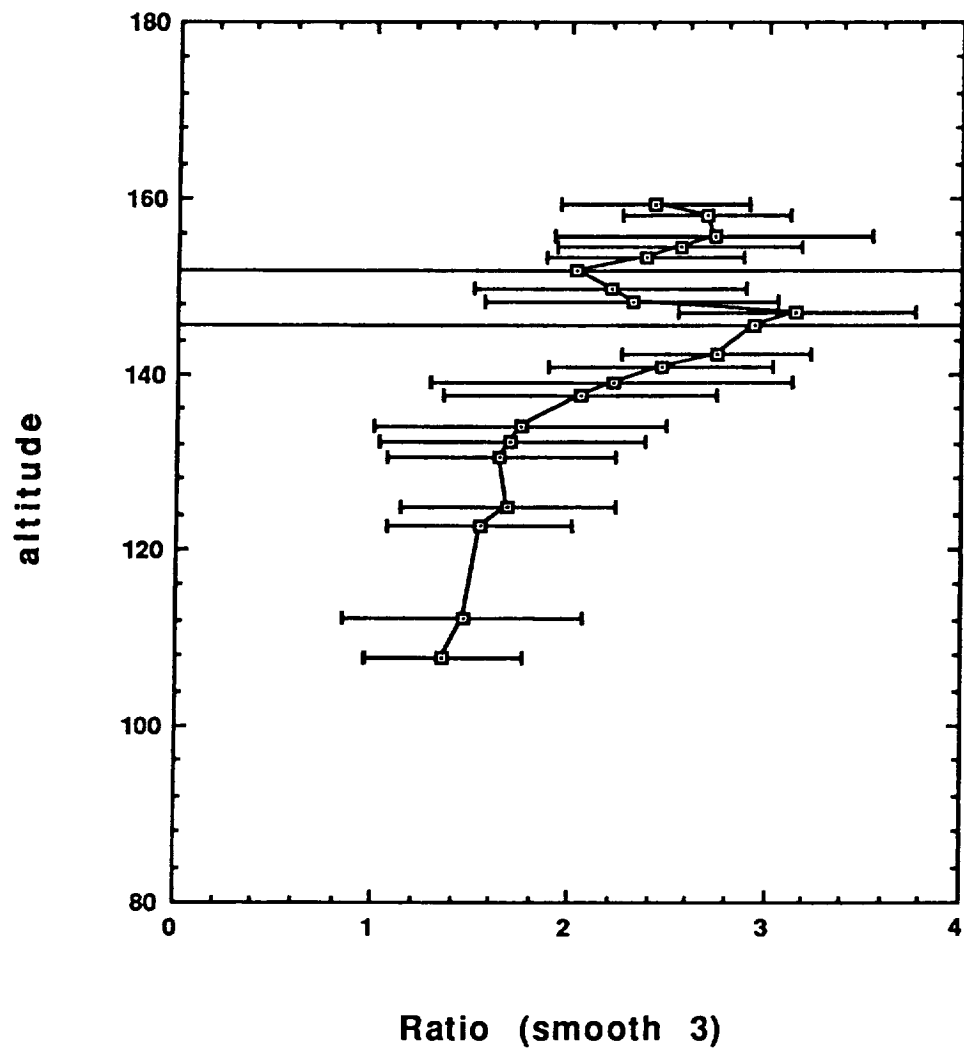


Figure 1

33.063 IMS NO^+/O_2^+

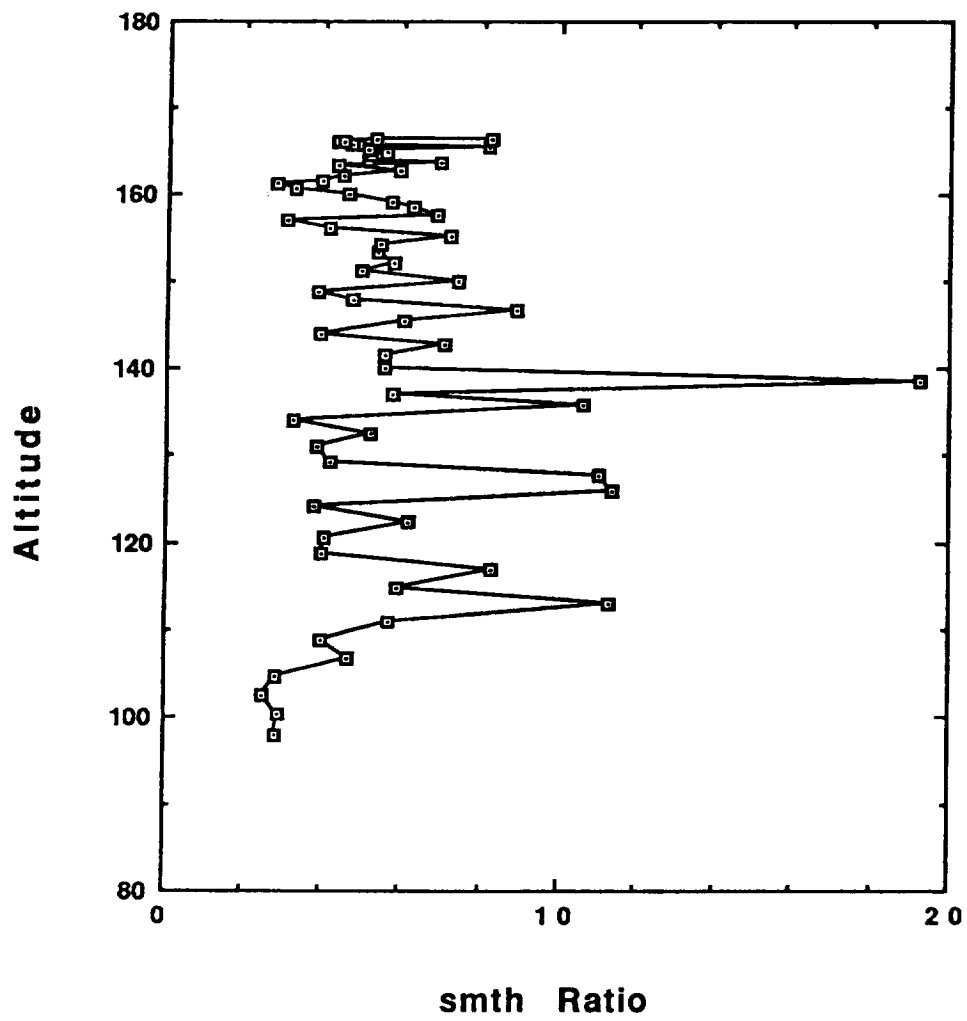
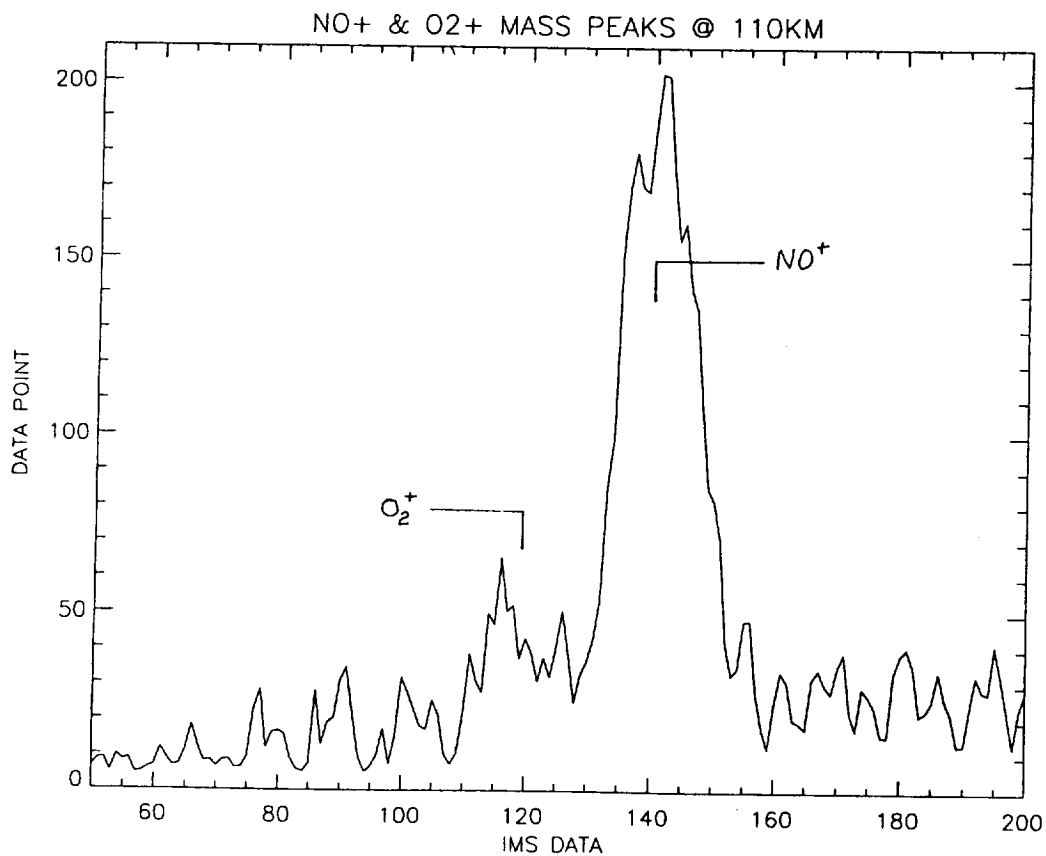
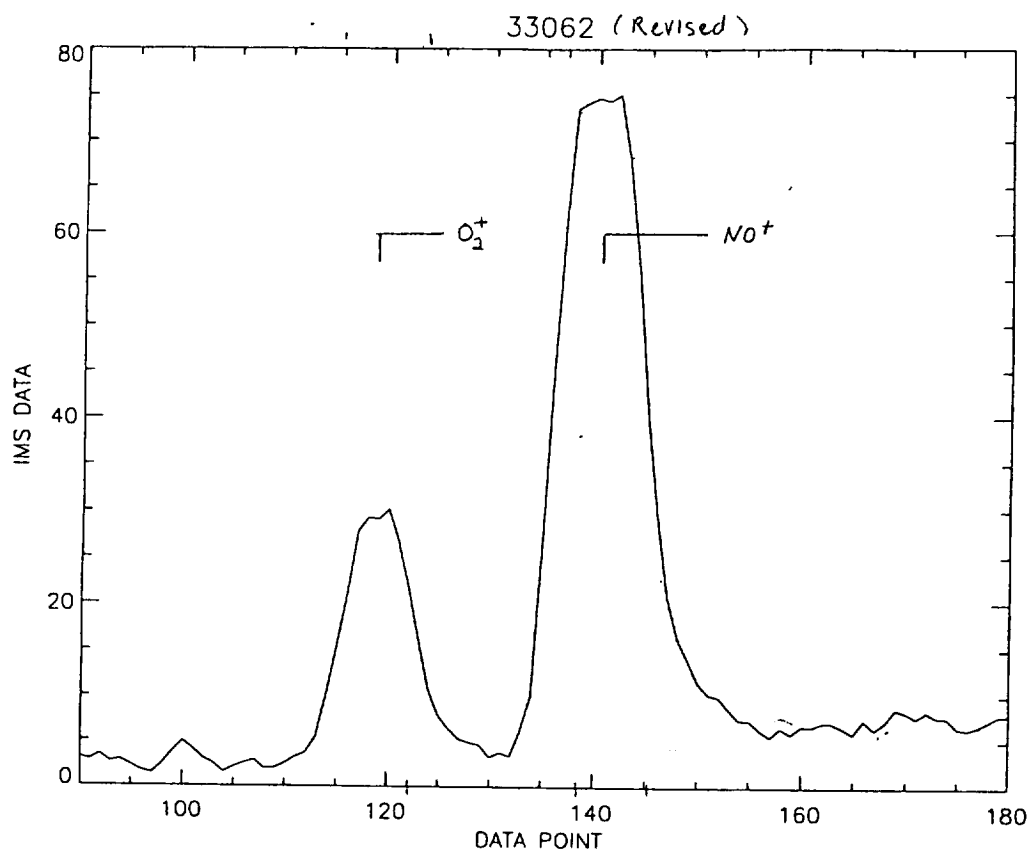


Figure 2



33.064 IMS NO⁺/O₂⁺

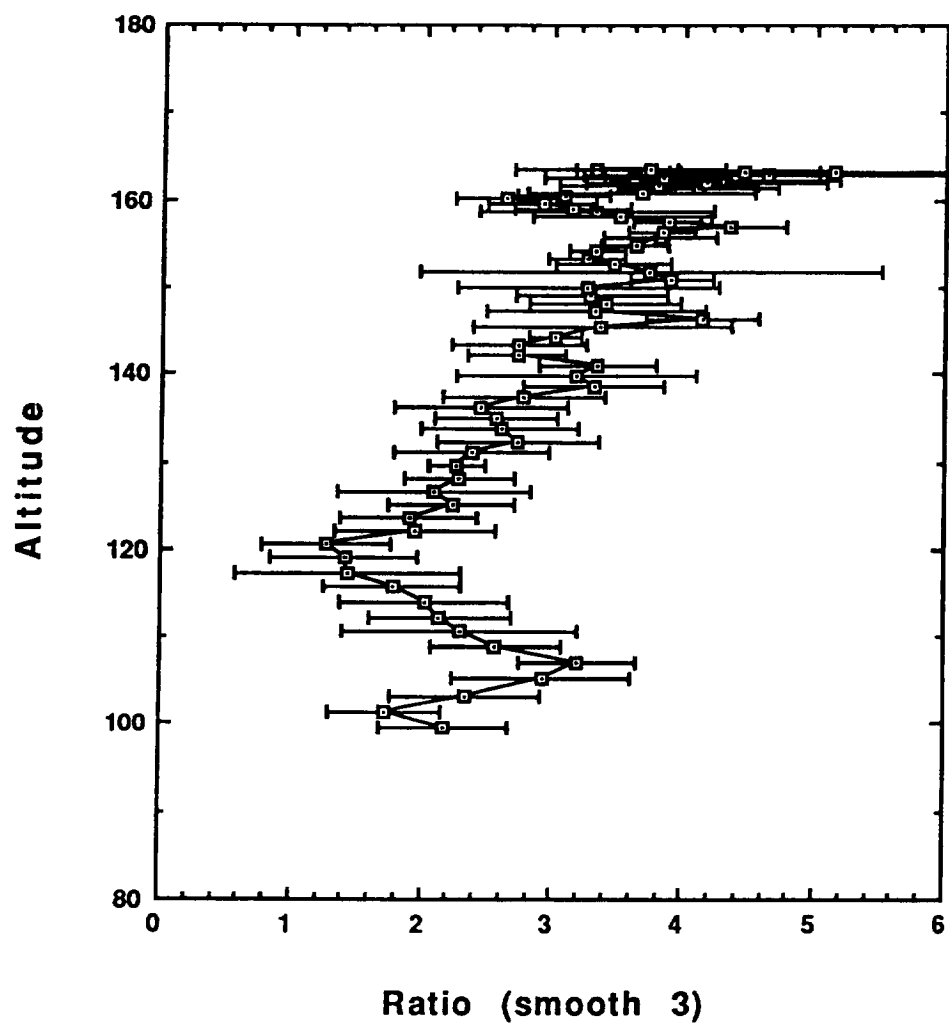


Figure 4

Data from "[O] upleg"

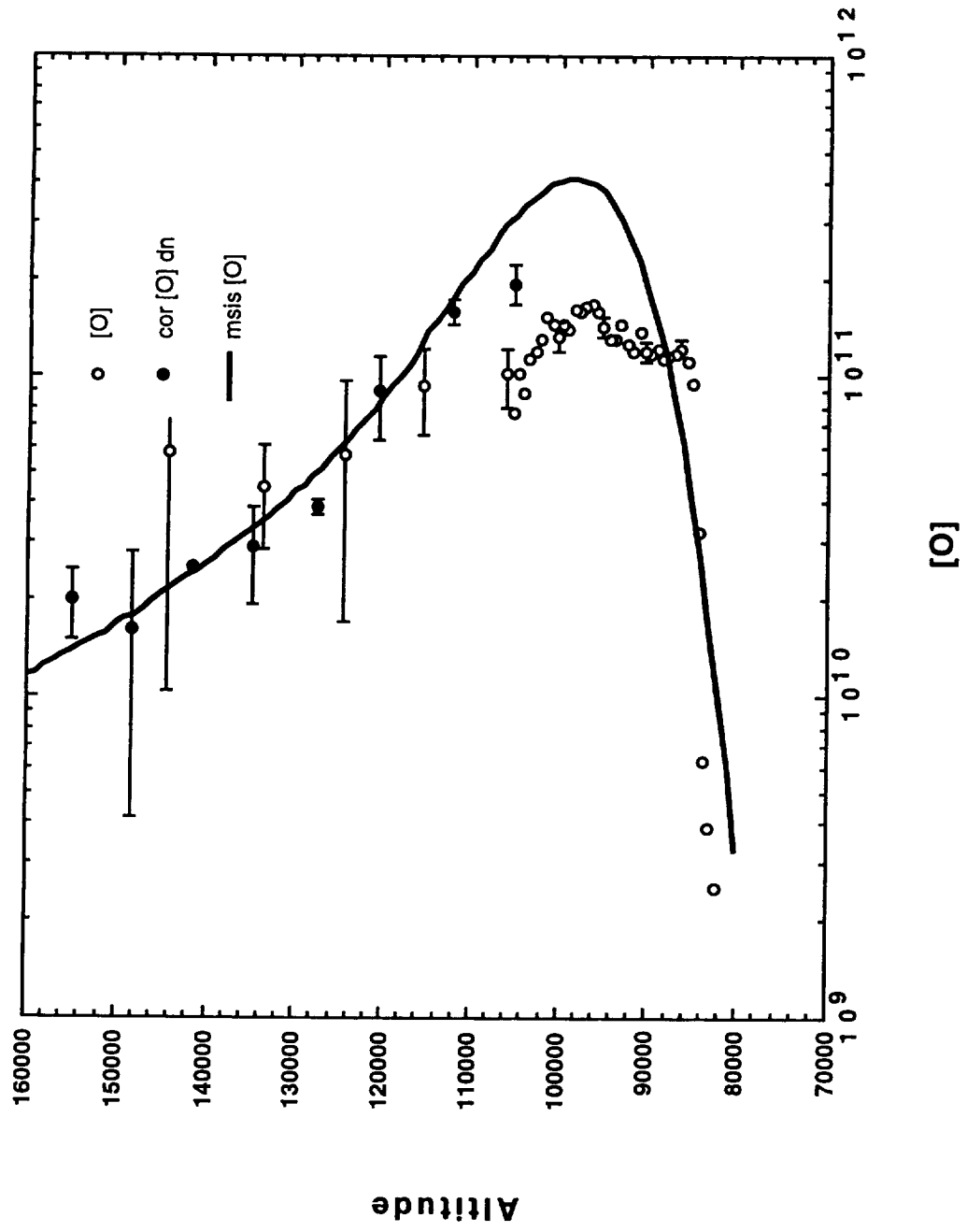


Figure 5

Depletion of oxygen in aurora: Evidence for a local mechanism

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Abstract. A ground-based and rocket investigation of the response of the neutral atmosphere to *E* region auroral heating has been carried out at Poker Flat, Alaska. The temporal evolution of the atomic oxygen to molecular nitrogen ratio (O/N_2) in the lower thermosphere has been monitored using the optical emissions from the aurora as a diagnostic. Comparisons between the changes in the O/N_2 ratio and the auroral Joule and particle heating have shown several examples of close similarity between the durations of the heating events and the depletions. Using the thermospheric winds measured during the rocket flights and the temporal structure of the depletions, the upper limit on the horizontal scale size of the depletions has been estimated at 200–400 km. Moreover, in situ rocket measurements of atomic oxygen showed significant differences at points separated horizontally by approximately 220 km. It is also concluded from the near coincidence between the depletion events and the Joule heating events that the dynamical mechanism(s) that drive the depletions were not far distant from the observing site, that is, local processes are sometimes dominant during periods of moderate auroral activity. We suggest that the observation of a strong wind shear in the 100- to 120-km altitude region [Larsen *et al.*, 1997] could be responsible for turbulence that contributes to the changes in minor constituent composition.

1. Introduction

Dissipation of electric currents (Joule heating) and precipitating energetic particles heat the lower thermosphere during aurora and drive vertical and horizontal transport of atmospheric gases [cf. Fuller-Rowell, 1985]. Upwelling in the resultant circulation cells brings oxygen poor air from below and causes a reduction in the atomic oxygen to molecular nitrogen ratio O/N_2 [Mayr and Volland, 1973; Hays *et al.*, 1973]. Downwelling results in the opposite effect observed as an increase in the O/N_2 ratio during geomagnetic storms [Burns *et al.*, 1995]. Although these are well known effects and are clearly evident in atmospheric models such as mass spectrometer and incoherent scatter (MSIS) [Hedin, 1983], comparisons between observations and models of the neutral atmospheric response to local auroral heating are in their infancy in part because of the difficulty of observing local composition changes and wind profiles in the lower thermosphere.

This paper will examine implications of ground-based and rocket-borne experiments designed to measure the variability of the lower thermospheric O/N_2 ratio during auroral heating events. The observations were carried out as part of the atmospheric response in aurora (ARIA) project at the Poker Flat Research Range, Alaska. The campaigns began with ARIA I in

March 1992 [Anderson *et al.*, 1995] and concluded with ARIA IV in November 1995. In this paper, data from some of these campaigns will be used to estimate the horizontal scale size of regions showing rapid and substantial changes in lower thermospheric composition during auroral heating events. The estimates are based on a ground-based optical technique for monitoring the time history of the O/N_2 ratio and direct rocket measurements of [O] and wind velocity.

Optical instrumentation at the launch site recorded the brightness of $N_2^+(427.8)$, $OI(844.6)$, $N_2(871.0)$, and $OI[630.0]$ transitions in the magnetic zenith. These radiances were combined following Hecht *et al.* [1989] and Gattinger *et al.* [1991] to infer the particle input energy flux (Q_p), the characteristic energy (E_0 , equal to the mean energy for a Maxwellian distribution), and to account for the effects of atmospheric scattering. An oxygen scale factor (f_0) has been derived that represents a multiplicative scaling of the [O] profile in the neutral model (MSIS-83) needed to match the observed brightness ratios. The N_2 profile was held fixed in the model.

Validation of the purely optical technique has been done utilizing the Sondre Stromfjord incoherent radar facility [Hecht *et al.*, 1991] and through comparisons with ARIA I rocket measurements of particle flux and composition [Hecht *et al.*, 1995]. The radar/optical technique, based on the radar measurement of the ionization profile, is used to estimate E_0 and optical ratios to ascertain f_0 . Errors are introduced into the purely optical approach because of its dependence on the emission from $OI[630.0]$ needed to obtain E_0 . However, the effects of uncertainties in the production of $OI[630]$ only weakly affect estimates of f_0 [Hecht *et al.*, 1989]. Similarly, if

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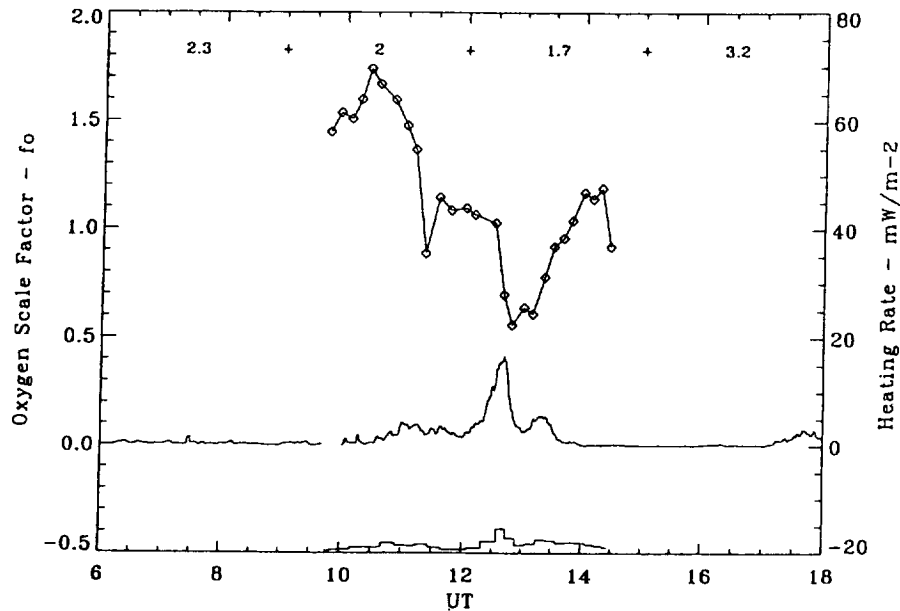


Figure 1. Observed (top) oxygen scale factor f_0 , (middle) the Joule heating rate Q_J , and (bottom) the particle heating rate Q_p traces for March 3, 1992, at Poker Flat, Alaska. The Q_p trace has been offset -20 mW m^{-2} for clarity. The 3-hour values of Kp are listed across the top of the plot. Local solar midnight is 10 UT. The ARIA I rocket was launched at 1404 UT.

the shape of the oxygen profile were to depart from diffusive equilibrium in the auroral event, an error would be introduced in the deduced E_0 but would only lead to a second-order effect on f_0 . Finally, since we are interested primarily in relative changes, errors in cross sections and rate constants lead to systematic errors in f_0 and are of secondary concern. As a result of comparing radar and rocket data for normal nightside aurora, we estimate the uncertainty in f_0 associated with using the purely optical approach to be 10 to 20% depending on the event. These uncertainties are comparable to those introduced by the two-parameter characterization of the energetic particle flux inherent in the technique; so while there are limitations, the purely optical technique provides a unique window on the variability of composition in the lower thermosphere that is available no other way.

Energy inputs into the atmosphere from both Joule heating and particle precipitation have been used in this study. To estimate the Joule heating rate Q_J , we have used the H magnetometer record from Poker Flat and followed the empirical prescription developed by Duboin and Kamide [1984]. They found from Chatanika incoherent scatter radar observations that the values of k in the relationship $Q_J = k \Delta H^2$ were $k = 10.5 \times 10^{-7} \text{ W m}^{-2} \text{ nT}^{-2}$ and $0.8 \times 10^{-7} \text{ W m}^{-2} \text{ nT}^{-2}$ for the eastward (premidnight) and westward (postmidnight) electrojets, respectively, where ΔH is the horizontal magnetic perturbation.

Energy input from precipitating energetic particles (primarily electrons) Q_p has been deduced from measurements of the auroral N_2^- (427.8 nm) brightness using a ground-based photometer viewing the magnetic zenith at Poker Flat. We have used a conversion factor of $4.3 \text{ mW m}^{-2} \text{ kR}$ [Hecht et al., 1995]. The particle heating rate is roughly 30% of the energy flux [Hays et al., 1973].

2. Observations

Figures 1–4 show time series of quantities observed during periods of auroral activity at Poker Flat, Alaska. The time

history of the oxygen scale factor f_0 (upper curve) was derived from the photometer observations of the aurora in the magnetic zenith. It represents changes in the O/N_2 ratio at altitudes between 110 and 140 km where the bulk of the auroral emissions originate. The f_0 data represent departures from a fixed reference model atmosphere, and hence the scale should be considered as relative. This is adequate for our purposes since it is the temporal behavior rather than absolute magnitude of the heating rate that is of interest in this paper.

The middle curve is an estimate of the local Joule heating rate Q_J , obtained from the Poker Flat magnetometer records using the method described above. The lower curve represents the heating rate from precipitating electrons Q_p inferred from the optical data plotted with a negative offset for clarity. The general level of geomagnetic activity is represented by the 3-hour Kp values shown along the top of the graphs.

The observations shown in Figure 1 (ARIA I) were obtained during relatively low geomagnetic activity with $Kp \approx 2$. The oxygen scale factor f_0 is clearly variable and uncorrelated with the local heating rate until the auroral event that began at approximately 1230 UT. Thereafter a decrease in f_0 of $\approx 40\%$ and recovery occurred on approximately the same timescale as the heating event, that is, 1 hour. Soon (10–15 min) after the heating rate reached a maximum, the O/N_2 as given by f_0 reached a minimum and immediately began to recover toward its presubstorm value.

A similar anticorrelated pattern of changes in f_0 associated with auroral heating events occurred for three isolated substorms in Figure 2. A decrease and recovery in f_0 is associated with the first event around 0700 UT. Again, the event between 0900 and 1000 UT shows the anticorrelation of f_0 and heating with the minimum in the O/N_2 occurring less than 30 min after the maximum in the heating rate. In the final event of the night beginning around 1200 UT, a decrease in f_0 follows the auroral heating. Observations were terminated because of sunrise, precluding observation of any recovery in f_0 .

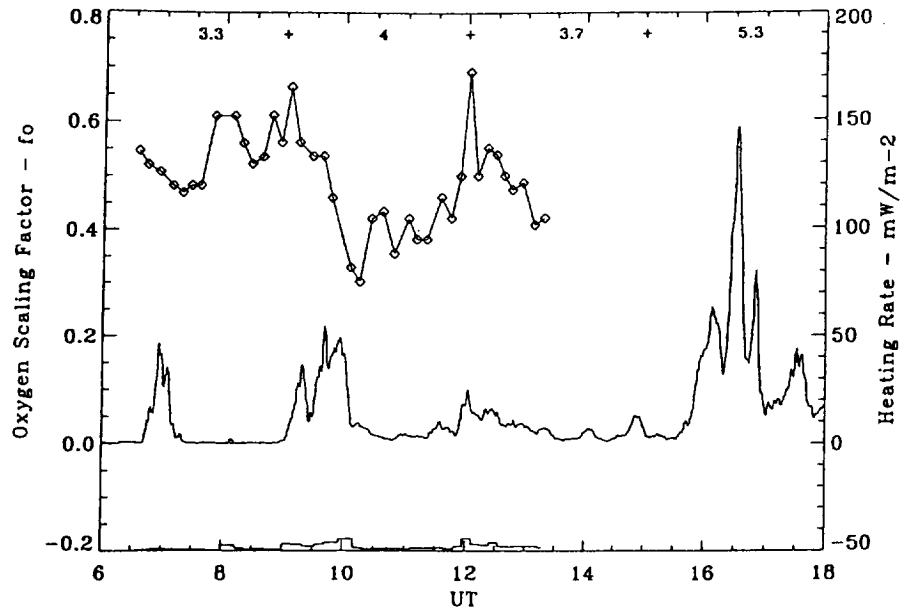


Figure 2. Observed auroral quantities for February 13, 1994. This was the day after the ARIA II rocket launch.

Observations shown in Figure 3 (ARIA II) were obtained during a moderately disturbed period. The clear anticorrelations evident in Figures 1 and 2 are much less obvious in this case. The decrease in O/N_2 in the period 0700–1000 UT, for example, did not track the heating rate in any obvious way, although there was some heating in the interval and f_0 did decrease. Also, a strong substorm with large heating occurred during the general decline in f_0 from 1200 to 1400 UT. So although declines in f_0 are associated with Joule heating in this example, the detailed tracking between them is gone.

There are two interesting aspects in the case shown in Figure 4 (ARIA IV). The most obvious is the uncorrelated behavior between f_0 and the heating for the large substorm at 1000–1200 UT. The O/N_2 ratio did not show any recovery following

the intense heating, rather it continued to decline throughout the night. However, the first substorm beginning at 0700 UT followed a period of extreme quiet conditions which had existed for several days. This substorm began before the sky was sufficiently dark to obtain optical measurements. However, when the instruments began to operate about 30 min later, the atmosphere was already showing a decline in O/N_2 . The long period of quiescent geomagnetic conditions suggests that the decline was a result of the heating event then in progress.

3. Discussion

The several cases of anticorrelation between heating and O/N_2 variations we have observed supports a cause and effect

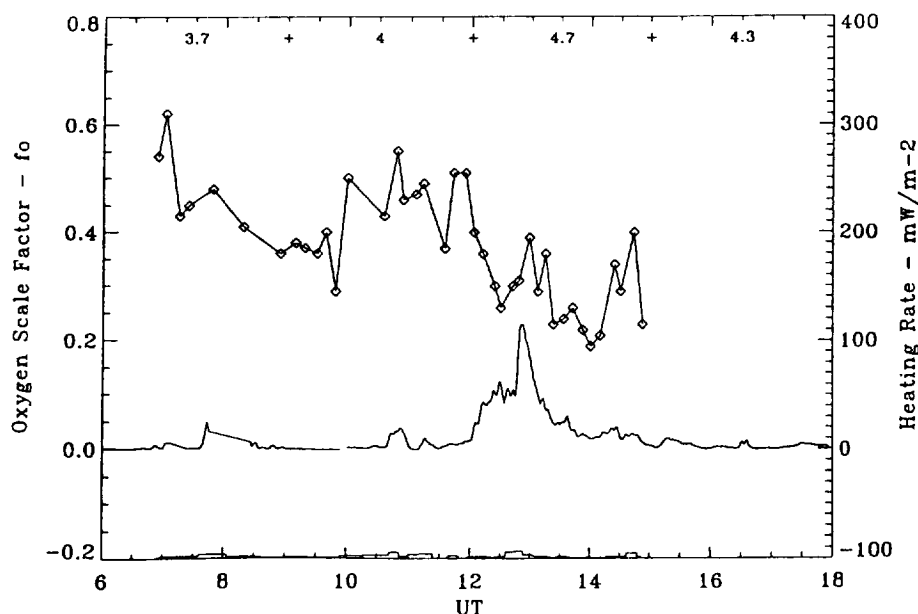


Figure 3. Observed auroral quantities for February 12, 1994. The ARIA II rocket was launched at 1316 UT.

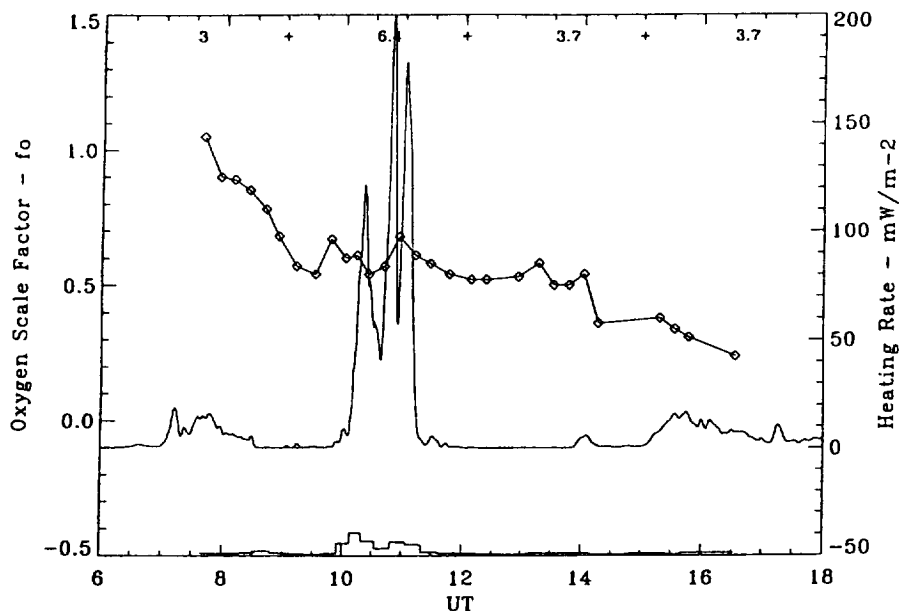


Figure 4. Observed auroral quantities for November 27, 1995. The ARIA IV rocket was launched into a premidnight aurora at 0807 UT.

relationship between them as expected from theory and modeling of the response of the thermosphere to auroral heating [cf. Hays *et al.*, 1973; Fuller-Rowell, 1985]. Furthermore, the timescale of the O/N_2 depletions as we have shown are comparable to the substorm timescales, that is, ~ 1 hour. There is a clear tendency, especially for the events in Figures 1 and 2, for the depletions to develop shortly after the heating starts and to begin recovery soon after the heating stops.

What does this observation reveal regarding the horizontal scale size of the depleted regions? We have an excellent measure of winds in the lower thermospheric region during diffuse aurora from chemical release rockets launched as part of the ARIA experiments [Larsen *et al.*, 1995, 1997; Odom *et al.*, 1997]. The measured wind speeds were approximately $50\text{--}100\text{ m s}^{-1}$ for the ARIA I and IV experiments at the launch times given in Figures 1 and 2; whereas, during the disturbed conditions of the ARIA II rockets, the winds were roughly twice as strong. The oxygen-depleted air parcels we observe could be the result of processes directly overhead or could be transported from a distant source. For either case the size of a depleted air parcel blowing across can be estimated from the product of duration of the depletion and the wind velocity, that is, approximately $(60\text{ min} \times 50\text{--}100\text{ m s}^{-1})$ $180\text{--}360\text{ km}$. This is also comparable to the scale size of the heated region in the case of ARIA I reported by Anderson *et al.* [1995].

In situ observations of neutral [O] on the ARIA I rocket were reported by Hecht *et al.* [1995]. Below 120 km the upleg and downleg profiles [Hecht *et al.*, 1995, Figure 3] diverged until at the peak near 100 km they differed by $2\times$, the downleg being the larger. The separation between the upleg and downleg was $\approx 220\text{ km}$. Hence these observations also yield a horizontal scale size which is consistent with that inferred from the ground-based observations.

How far away did the depleted region originate? The time delays between the maximum heating and the maximum depletion were found to be tens of minutes, suggesting that the source region if not overhead was no more than approximately $(30\text{ min} \times 50\text{--}100\text{ m s}^{-1})$ $90\text{--}180\text{ km}$ distant. The response

noted in Figure 4 (ARIA-IV) is also consistent with this interpretation. The magnetic activity had been very low prior to the heating event so we would not expect that depleted air from other parts of the polar region would be responsible for the initial decrease in O/N_2 following 0730 UT. Moreover, the winds would have been less intense and the resultant transport distances would imply a local source of depleted air.

The lack of anticorrelation for the magnetically active periods represented by Figure 3 (ARIA II) and the midnight sector activity in Figure 4 (ARIA IV) leaves open the question of the scale of the depleted air parcels and distance to the source region. Effects due to nonlocal, global scale processes are expected during periods of substantial magnetic activity. For example, the general decline in O/N_2 throughout the night evident in ARIA II is consistent with a thermosphere ionosphere general circulation model run for that event (H. Elliott, private communication, 1996). Hence the set of observations presented clearly establishes that the mechanism(s) responsible for the depletion of oxygen in these aurora is (are) sometimes local and operative at or in the vicinity of the observation site at Poker Flat. At other times a local signature is not evident in the data, and nonlocal processes and transport dominate.

Modeling of the local response results presents a challenge. A recent example is found in the results of Sun *et al.* [1995]. Using a three-dimensional, high-resolution model and a rather extensive set of geophysical inputs based on the ARIA I experiment, they were unable to reproduce the compositional changes observed. Even though the calculated vertical winds seem reasonable compared with the ARIA II wind divergence measurements [Odom *et al.*, 1997], the calculated change in the O/N_2 is an order of magnitude too small.

An argument could be made, however, that multiple processes are at work that couple the compositional response and the dynamical structures in the diffuse aurora that are not included in the models. Consider, for example, a possible consequence of the *E* region wind shears we have observed in the 100- to 120-km altitude range [cf. Larsen *et al.*, 1995, 1997]. The

layer meets the Richardson instability criterion ($R < 0.25$) and could spawn unstable waves resulting in turbulent mixing. The resultant modification of the eddy diffusivity would likely modify the minor constituent concentrations. The magnitude of the change in diffusion rates can be estimated from the following considerations.

When $\partial^2 n / \partial z^2 \gg n / (H)^2$, the rate of the diffusion of a minor species n is approximately $K \partial^2 n / \partial z^2$, where K is the diffusion coefficient. Using U.S. Standard Atmosphere atomic oxygen profiles, we estimate $\partial^2 n / \partial z^2 \sim 5 \times 10^{-9} \text{ m}^{-2} n$ between ~ 110 km and 140 km. This gives a diffusion timescale of $\tau \sim 2 \times 10^8 \text{ m}^2 K^{-1} [\text{m}^2 \text{ s}^{-1}]$. A nominal value of K in the lower thermosphere obtained from the U.S. Standard Atmosphere is $\sim 2 \times 10^2 \text{ m}^2 \text{ s}^{-1}$. We use this value as a reference (K_{ref}). The value K_{ref} gives $\tau \sim 10^6 \text{ s} \sim 10$ days. For a value of K which is 100 times K_{ref} , τ is reduced to $\sim 10^4 \text{ s} \sim 3$ hours. Timescales of the order of tens of minutes (commensurate with the ARIA observations) are achieved when K approaches values of the order of $1000 K_{\text{ref}}$. The value K_{ref} is a space and time average, whereas turbulence is localized and intermittent. Locally, K should be much greater than K_{ref} . For example, if active turbulence generation occurs $\sim 1\%$ of the time (or over 1% of the volume), local values of K should be $\sim 100 K_{\text{ref}}$. Values of this order have been inferred from measurements [Hocking, 1985, and references therein]. The value of molecular diffusivity (K_m) places a lower limit on the local value of K . In the upper part of the region of interest, values of K_m are quite large. For example, above ~ 130 km, K_m exceeds $\sim 1000 K_{\text{ref}}$. Thus K must be of the order of $1000 K_{\text{ref}}$ to produce timescales of the order of 10 minutes, but to have an effect on composition change above ~ 130 km, K must be even greater. Thus turbulence producing the observed changes in composition would most likely have values of $\sim 1000 K_{\text{ref}}$ and occur below ~ 130 km. The strongest shears associated with the dramatic wind feature seen in the ARIA data occur below 130 km, are very unstable through a deep layer, and suggest very vigorous turbulence generation. In such a region, values of $K \partial^2 n / \partial z^2$ large enough to produce the observed changes in composition seem realizable.

4. Conclusions

We conclude that for simple events such as illustrated in Figures 1 and 2 that parcels of air in the lower thermosphere are subjected to processes that result in significantly lowered O/N_2 ratios and that the scale size of these parcels is of the order of a few hundred kilometers. Furthermore, the source region for the depletions appears to be not far removed from the observation site where Joule and particle heating are occurring; that is, local mechanisms are involved. During magnetically disturbed conditions, changes in the thermospheric composition tend to lose the signature of local sources and are more probably the result of nonlocal and perhaps global transport processes.

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Coupling between Neutral and Ionized Nitric Oxide in the Polar Thermosphere

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The density of ionized nitric oxide in the lower thermosphere is coupled to the density of neutral nitric oxide through the two ionospheric reactions: the dissociative recombination of ionized nitric oxide and the charge transfer of ionized molecular oxygen to nitric oxide. The ratio of the ionized nitric oxide density to the ionized molecular oxygen density is directly proportional to the neutral nitric oxide density and the reaction rate of the charge transfer reaction, and inversely proportional to the reaction rate of the dissociative recombination reaction. This relationship has been tested using a photochemical model that includes the effects of auroral electrons, solar soft x-rays, photoelectrons, excited nitrogen atoms, odd nitrogen reactions, ionospheric reactions, and vertical transport. The results show that while the neutral nitric oxide density is not sensitive to the rate of the dissociative recombination reaction, the NO^+/O_2^+ ratio is very sensitive to this rate. The model was compared to the results of a June 1994 Poker Flat rocket experiment which made simultaneous measurements of the ion density ratio and the neutral nitric oxide density. The results of the comparison indicate that in order to fit the rocket data, the rate of the dissociative recombination reaction needs to be higher than the value measured in laboratory experiments. The June 1994 rocket experiment was conducted at a time of high nitric oxide density. A second experiment is planned for a time of low nitric oxide density.

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